Three Forks

Enhanced Hydraulic Analysis and Floodplain Mapping Report

Gallatin County, MT

June 2020

Michael Baker INTERNATIONAL

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Enhanced Hydraulic Analysis And Floodplain Mapping

Gallatin County, MT

Prepared For:

Montana Department of Natural Resources and Conservation

Prepared By:

Michael Baker International

Document History

Document Location

Location

Revision History

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Cover Photograph:

Jefferson River side channel near confluence with Missouri River.

Cover Photograph Credit:
Morrison-Maierle, Inc.

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APPENDIX

1. Introduction and Background

As part of a Mapping Activity Statement (MAS) contract initiated by the Montana Department of Natural Resources and Conservation (DNRC), Michael Baker International has completed detailed hydraulic analyses of the Madison River, the Jefferson River, and associated split flows in the vicinity of the City of Three Forks in Gallatin County, Montana. The purpose of this report is to document the hydraulic analyses and to provide results for subsequent floodplain mapping analyses. Results of the analyses will be incorporated into the Gallatin County, MT, and Incorporated Areas Digital Flood Insurance Rate Map (DFIRM) and Flood Insurance Study (FIS) (**Reference 1**). **Appendix A** includes the Certification of Compliance form that confirms the study has been completed using sound and accepted engineering practices and is in compliance with all contract documents.

A list of primary flooding sources included in this hydraulic study is provided in **Table 1-1**, and a map showing these flooding sources is provided in **Figure 1-1**. It should be noted that these primary flooding sources are not the only flooding sources included in this study. Several flows split from these flooding sources to form secondary flooding sources. These split flows are detailed in **Section 3** of this report. This study represents a revision to the effective study, which is based on analyses performed by David Smith and Associates, dated January 14th, 2003, as well as analyses performed by Van Mullem Engineering, dated May 2003 and revised on May 16th, 2004. The effective study is detailed (Zone AE) in the vicinity of the City of Three Forks: on the Jefferson River between Frontage Road and approximately 1.1 miles downstream of Interstate 90, and on the Madison River between approximately 1.2 miles upstream of Interstate 90 and approximately 1.0 mile downstream of Interstate 90. Outside of these limits, the effective study is approximate (Zone A). The effective study also includes some areas of unknown flood risk (Zone D) outside of the detailed study limits.

The new study documented in this report includes approximately 15.3 miles of enhanced analysis with floodway on the Jefferson River from approximately 500 feet downstream of Meridian Road to approximately 900 feet upstream of the Gallatin River. It also includes approximately 11.7 miles of enhanced analysis with floodway on the Madison River from approximately 1.1 miles upstream of Climbing Arrow Road to the confluence with the Jefferson River. This study also includes approximately 6.7 miles of enhanced analysis of flow splits associated with the Jefferson and Madison Rivers. The hydraulic analysis was completed using peak discharges for the 10-, 4-, 2-, 1-, and 0.2-percent-annual-chance (10-, 25-, 50-, 100-, and 500-year) flood events, as well as the 1-percent-plus-annual-chance event.

Table 1-1: Flooding Sources Studied

Flooding Source	Upstream Limit	Downstream Limit	Reach Length (Miles)
Jefferson River	Approximately 500 feet downstream of Meridian Road	Approximately 900 feet upstream of the confluence with the Gallatin River	15.3
Madison River	Approximately 1.1 miles upstream of Climbing Arrow Road	Confluence with the Jefferson River	11.7

For this project, multiple contractors were involved in the delivery of the many components that comprise the Technical Support Data Notebook (TSDN). Morrison-Maierle, Inc. completed the field surveying tasks for all flooding sources in the project area (**Reference 2, Reference 3, and Reference 4**). The Morrison-Maierle tasks included the collection of cross-section bathymetric survey data and hydraulic structure data. The topographic data collection was provided by Quantum Spatial (**References 5 and Reference 6**). Michael Baker International (Baker) completed the hydrologic analyses for basins in the Madison River watershed (HUC 8) (**Reference 7**) and the Jefferson River Watershed (Reference **8**). The topographic, field survey, and hydrologic data were reviewed and approved by FEMA during the process of the hydraulic and floodplain mapping analyses. Detailed information regarding Morrison-Maierle, Quantum Spatial, and Baker contributions to the TSDN are included in the appropriate sections of this report.

1.1. Community Description

Three Forks is located in southwest Montana in Gallatin County, near the confluence of the Madison, Jefferson and Gallatin Rivers. These rivers are the headwaters of the Missouri River, which begins at their confluence. Located near the western border of Gallatin County, the counties that are nearest the Three Forks study area are: 1) Broadwater County to the north, 2) Jefferson County to the west, and 3) Madison County to the south. The City of Three Forks is the third largest city in Gallatin County.

Gallatin County and Three Forks have experienced moderate- to substantial population growth in the past 19 years. **Table 1-2** summarizes the Census population data (**Reference 9 - 13**). **Table 1-3** summarizes the census housing unit estimates (**References 9 - 13**). There has been substantially more population growth in Gallatin County compared to Three Forks since 2000 with increases in population of 325 (18.8%) and 44,045 (64.9%) for Three Forks and Gallatin County, respectively, between 2000 and 2018 (**Reference 9 and Reference 10**). There have been significant increases in the number of estimated housing units in Three Forks and Gallatin County since 2000 with an additional 158 units (Three Forks) and 21,522 units (Gallatin County) added (note that the recent census housing unit data are only available through year 2017 for Three Forks but are available through year 2018 for Gallatin County). With the availability of vastly improved terrain data (through

Light Detection and Ranging (LiDAR) and recent bathymetric survey), hydraulic modeling capabilities (two-dimensional in complex flow areas), and increased hydrologic data (up to 35 additional years of flow records), a restudy in the Three Forks community is needed. This study will help residents, community officials, emergency management, and local, state, and federal agencies understand the impacts of living and working near the Madison River, Jefferson River, and their associated flow splits, as well as the potential flood impacts on the physical assets of the community.

Table 1-2: Census Population Estimates

Community	2000 Population	2010 Population	% Increase from 2000 to 2010	2018 Population Estimate	% Increase from 2010 to 2018
Three Forks	1,728	1,869	8%	2,053	9.8%
Gallatin County	67,831	89,513	32%	111,876	25%

Table 1-3: Census Housing Units Estimates

Community	2000 Housing Units	2010 Housing Units	% Increase from 2000 to 2010	Housing Unit Estimate (2017 Three Forks, 2018 Gallatin County)	% Increase from 2010
Three Forks	726	850	17.1%	884	4.0%
Gallatin County	29,489	42,289	43.4%	51,011	20.6%

Most severe flooding events in the Madison and Jefferson River watersheds have been the result of spring snowmelt or ice jams. Historically, notable flooding within this watershed has occurred numerous times. Ice jamming can occur at road crossing, natural constrictions, at other locations when topographic features or freezing patterns support the formation of jams. Baker has prepared a separate document (Three Forks Ice Jam Analysis, **Appendix I**) describing historic ice jam events in the vicinity of Three Forks and detail of the ice jam analyses and results that are reported in later sections of this report.

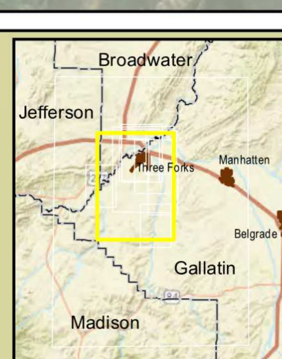
Above the study area are three significant impoundments on the Madison River: 1) Ennis Lake, a reservoir formed by Madison Dam on the Madison River just below the town of Ennis, MT, owned by Northwestern Energy, and initially closed in 1901, 2) Hebgen Lake which is an impoundment located below West Yellowstone, MT, created in 1914 and stores and regulates flows for downstream water users and power generation, and 3) Earthquake Lake, an impoundment immediately below Hebgen Lake which was created by a landslide caused by the 1959 Hebgen Lake earthquake.

There are no impoundments on the Jefferson River, but two major impoundments are located within the watershed: Clark Canyon Dam and Reservoir on the Beaverhead River, and the Ruby Dam and Reservoir on the Ruby River. Clark Canyon Dam was completed in 1964, and the reservoir stores approximately 257,000 acre-ft. The Ruby Dam was completed in 1938, and the capacity of Ruby Reservoir is about 37,600 acre-ft.

Updated Flood Frequency Analyses were performed for stream gages in the study area, which utilized Bulletin 17c flood frequency analysis methods and applied record extension methods (Maintenance of Variance Extension Type III (MOVE.3)) for the analyses. There is currently one active USGS Gaging station within the study area (USGS 06036650 Jefferson River near Three Forks, MT) and one historic USGS gaging station within the study area (USGS 06042500 Madison River near Three Forks, MT). The Jefferson River gage came online in 1978 while the Madison River gage was in service from 1893 until 1950. Both gages were used for watershed-wide hydrologic updates to the Jefferson River and Madison River watersheds. The results of the updated flood frequency analyses and additional analyses utilized to establish discharges for this analysis are reported in the 2018 Baker Hydrologic reports (**References 7 and 8**). At the Jefferson River gage, the highest gaged peak flow was nearly a 4% annual chance flow (17,400 cfs in 2011), with other peak flows below the 4% annual chance flood (17,000 cfs and 16,700 cfs in 1995, and 1997, respectively). At the Madison River stream gage, the two highest peak flows were between the 10% and 4% annual chance floods (8,175 cfs and 7,840 cfs in 1896 and 1943, respectively). Stream gage locations, watershed delineations, and flow recommendations are provided in **Appendix D**.

LEGEND

- City Town
- Railroad Embankment
- Three Forks Levees
- StudyLimits
- Profile Baseline
- Stream



DATA FRAME PROPERTIES:
Coordinate System: NAD 1983 StatePlane Montana FIPS 2500 Feet
Projection: Lambert Conformal Conic
Datum: North American 1983
Units: Foot US

0 0.4 0.8 1.6 Miles

Three Forks

Figure 1-1:

Flooding Source Locations

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11/22/2019

1.2. Basin Description

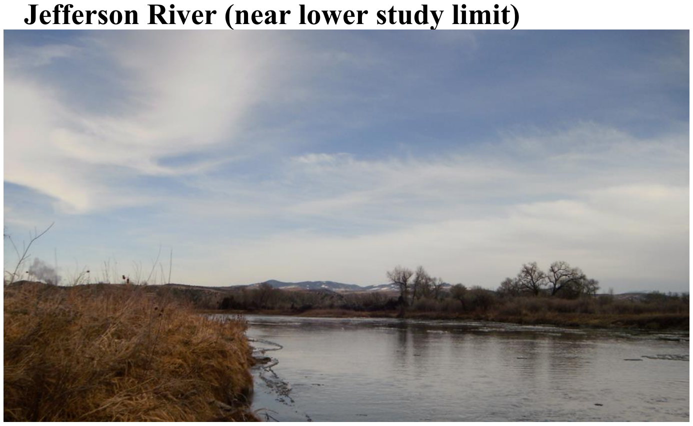
The Jefferson River and the Madison River, along with the Gallatin River, are the three headwater tributaries that form the Missouri River near the City of Three Forks, Montana. Much of the land along the Madison and Jefferson Rivers and their associated tributaries are in private ownership; primarily as farms, ranches, and the businesses and residents of the communities along the rivers. Throughout the remainder of these watersheds, however, most of the land ownership is public land - managed primarily by the US Forest Service, Bureau of Land Management, and State of Montana.

1.2.1. Madison River Watershed

Figure 1-2: Madison River at Climbing Arrow Road (near upper study limit)

As reported in the 2018 Baker hydrology report (**Reference 7**), the Madison River watershed drains a substantial portion of southwest Montana and includes portions of northwest Wyoming in Yellowstone National Park. The Madison River begins at the confluence of the Gibbon and Fire Hole Rivers in Yellowstone National Park, WY, approximately 13 miles upstream of West Yellowstone. The tributaries to the Madison River drain the continental divide in the southern portion of the watershed (Firehole River), as well as the Gravelly Range and Madison Range along the western and eastern portions of the watershed, respectively. The Madison River watershed at USGS gaging station near Three Forks, MT (USGS 06042500) drains approximately 2,516 mi^2.

Figure 1-3: Madison River near confluence with Jefferson River (near lower study limit)



Above the study reach, Hebgen Lake is impounded by Hebgen Dam, completed in 1914 by Montana Power Company. Hebgen Dam is approximately 85 feet tall and provides approximately 325,000 acre-feet storage in Hebgen Lake. Hebgen Dam is operated as a hydro-electric facility by NorthWestern Energy. Earthquake Lake was formed as a result of a landslide triggered by the August 1959 magnitude 7.5 earthquake along the Madison Fault near Hebgen Lake. The US Army Corps of Engineers have performed various projects to improve stabilization of the debris that forms Earthquake Lake. As a result of a natural geologic event, there are no flow control mechanisms out of Earthquake Lake, with stabilization efforts focused primarily on the outlet of Earthquake Lake. Concern about erosion through and downstream from the Earthquake Lake splillway resulted in operational limitations on flows into Earthquake Lake (Hebgen Dam outlet) to limit Madison River flows below Earthquake Lake at USGS Gage 06038800 (Madison River at Kirby Ranch near Cameron, MT) to 3,500 cfs. However, flood events of 1993, 1996, and 1997 exceeded this threshold.

The Madison River watershed elevation ranges from just over 4,000 feet at the confluence with the Jefferson River, to approximately 4,160 feet at USGS gaging station 06042500 (Madison River near Three Forks MT), and over 11,000 feet in the watershed's mountain peaks. The mean basin elevation is 7,115 feet, and 76% of the basin is at an elevation above 6,000 ft. Approximately 41% of the watershed is forested. Annual precipitation varies widely across the watershed, with up to 50 inches per year in the high mountains and as low as 12 inches per year at the Madison River valley floor. Based on data collected using USGS StreamStats (**Reference 14**), mean annual precipitation averaged across the watershed is 28.7 inches per year. Temperatures vary widely across the watershed as well, with wintertime low temperatures frequently dropping well below zero degrees Fahrenheit, and summertime high temperatures average more than 80°F in the watershed's lower elevations (Montana Climate Office).

Figure 1-4: Madison River near Interstate 90

In the study area, the Madison River above Interstate 90 is confined by a large bluff on west side, and a non-certified levee of the east side. Downstream of Interstate 90, the Madison River is confined by a railroad embankment to the west (which separates it from the Jefferson River), and high ground to the east. Throughout the study reach, the river has a consistently mild slope, with a moderate amount of stream braiding and secondary flowpaths. The width and shape of the main river channel is relatively consistent throughout the Madison River study reach.

1.2.2. Jefferson River Watershed

The Jefferson River watershed drains a substantial portion of southwest Montana from the Madison River watershed along the Continental Divide and border with Idaho to the West. It forms at the confluence of the Beaverhead and Big Hole Rivers near Twin Bridges, MT, approximately 60 miles upstream of Three Forks. The tributaries to the Jefferson River drain the continental divide to the west (Big Hole River) and south (Beaverhead River), as well as portions of the Elkhorn Mountains (Boulder River) and the Ruby Range, Gravelly Range, and Tobacco Root Mountains (Ruby River). The Jefferson River watershed at USGS gaging station near Three Forks, MT (USGS 06036650) drains approximately 9,560 mi^2.

From its source near Twin Bridges, the Jefferson River is a relatively low gradient, meandering river anastomosed with multiple flow splits around well vegetated, quasi-permanent islands. The Jefferson River contains broad floodplains, which are inundated during relatively high flows that overtop the streambanks and continue as shallow overland flow and relic channel features. The floodplains have strong connectivity with the Jefferson River through the shallow ground water table present during the spring and early summer peak flows. The lower reaches of the major tributaries to the Jefferson River (Big Hole, Beaverhead, and Ruby Rivers) share similar characteristics with the Jefferson River (low gradient, meandering channel, broad floodplains). Only the headwater streams and creeks which feed these tributaries have steep, higher gradient channels characteristic of headwater streams.

Figure 1-5: Jefferson River near Meridian Road (near upstream limit of study)

Much of the land use adjacent to the Jefferson River and floodplain is classified as agricultural (farming and ranching). While several small farming communities are present along the Jefferson River, the setting is almost entirely rural, with Three Forks having the highest population (approximately 2,053 (US Census Bureau 2018 estimated)) followed by Whitehall (approximately 1,100), Twin Bridges (approximately 400), Willow Creek (approximately 200), and Cardwell (approximately 40). The largest community within the Jefferson River watershed is Dillon, MT (along the Beaverhead River) with a population of just under 4,300. US Highway 287, State Highway 55, State Highway 41, and Interstate 90 are the major roadways present along portions of the Jefferson River. These roadways, as well as numerous county roads, city streets, private drives, farm/ranch accesses, and the Montana Rail Link railroad have bridges that cross the Jefferson River.

Several small irrigation systems divert water from the Jefferson River, but these appear to be relatively minor diversions and generally deliver water to farms and ranches within, or very near, the Jefferson River floodplain. There are no impoundments on the Jefferson River, but two major impoundments are located within the watershed: Clark Canyon Dam and Reservoir on the Beaverhead River, and the Ruby Dam and Reservoir on the Ruby River. Clark Canyon Dam was completed in 1964, and the reservoir stores approximately 257,000 acre-ft. The Ruby Dam was completed in 1938, and the capacity of Ruby Reservoir is about 37,600 acre-ft. As noted above, much of the land along the Jefferson River and its tributaries is in private ownership; primarily as farms, ranches, and the businesses and residents of the communities along the rivers. Throughout the remainder of the watershed, however, most of the land ownership is public land - managed primarily by the US Forest Service, Bureau of Land Management, and State of Montana.

Figure 1-6: Jefferson River near confluence with Gallatin River (near downstream study boundary)

The Jefferson River watershed elevation ranges from 4,077 feet at USGS gaging station 06036650 (Jefferson River near Three Forks, MT), to over 11,000 feet in the watershed's mountain peaks. The mean basin elevation is 6,750 feet, and 75% of the basin is at an elevation above 6,000 ft. Approximately 33% of the watershed is forested. Annual precipitation varies widely across the watershed, with up to 50 inches per year in the high mountains and as low as 12 inches per year at the Jefferson River valley floor. Based on data collected using USGS StreamStats (**Reference 14**), mean annual precipitation averaged across the watershed is 19.6 inches per year. Temperatures vary widely across the watershed as well, with wintertime low temperatures frequently dropping well below zero degrees Fahrenheit, and summertime high temperatures average more than 80°F in the watershed's lower elevations (Montana Climate Office).

1.3. Previous Studies

This study represents a revision to the effective study, which is based on analyses performed by David Smith and Associates, dated January 14th, 2003, as well as analyses performed by Van Mullem Engineering, dated May 2003 and revised on May 16th, 2004. The effective study is detailed (Zone AE) in the vicinity of the City of Three Forks: on the Jefferson River between Frontage Road and approximately 1.1 miles downstream of Interstate 90, and on the Madison River between approximately 1.2 miles upstream of Interstate 90 and approximately 1.0 mile downstream of Interstate 90. Outside of these limits, the effective study is approximate (Zone A). The effective study also includes some areas of unknown flood risk (Zone D) outside of the detailed study limits.

1.4. Flood History

Consistent with many river systems in the Rocky Mountain region, peak flows on the Madison River and tributaries typically are a function of annual snowmelt and generally occur in the late spring or early summer. As an example, of the 57 years of peak flow records at USGS 06041000 Madison River below Ennis Lake, near McAllister, MT, all the annual peak flow events exceeding the 50% Annual Exceedance Probability (AEP) (4,760 cfs) occur in May or June. This dominance of spring/summer snowmelt on the annual peak flow record is reflected by other stream gages in watersheds within the region. **Table 1-4** shows the highest recorded peak flow on the Madison River at the USGS gage near Three Forks (Gage No. 06042500).

Table 1-4: Flood History on the Madison River

Madison River		
Station Name	Madison River near Three Forks	
Station Number	06042500	
Period of Peak Flow Data	1894–1950	
Number of Peak Flow Records	16	
Largest Recorded Events	Date	Peak Flow (cfs)
	6/19/1896	8,175
	6/2/1943	7,840
	6/2/1894	6,980
	6/10/1942	6,650
	6/11/1947	6,540

In addition to flooding from snowmelt, the Madison River near Three Forks has historically experienced ice-affected flooding events, which commonly occur during extreme cold periods from December to

March and are largely composed of frazil and anchor ice. The first clear description of ice-affected flooding on the Madison River was provided by J.C. Stevens in 1922 where he provided the following:

> "The Madison River…flows through two agricultural valleys locally known as the Upper and Lower Madison Valleys. In these valleys the river banks are low, and near the lower end of each valley the river divides and subdivides into a network of many brush-lined channels.
>
> "In these many channeled parts of each valley, during the cold winter months, ice gorges of varying characteristics are formed. These gorges frequently cause the river to leave its channel entirely and flow across the valley floor, occasionally driving the residents from their homes and leaving the valley covered with solidified frazil ice many feet in thickness.
>
> "The winter of 1916-1917 was one of exceptionally sustained, moderately low temperatures, during which an unusual quantity of frazil and anchor ice was formed. This resulted in ice gorges and extensive overflow of agricultural lands in both valleys."
>
> "The Madison is probably the largest river in the state in which river overflow conditions [caused by ice gorges] are so pronounced. The reasons are not hard to find. Madison River has a fairly steep gradient throughout its course. In the two valleys the banks are low, the river is shallow and wide, and the bed is strewn with boulders, cobble stones and gravel."

Stevens' description is not unlike local reports of Madison River ice gorging today that regularly occurs near Ennis in the Upper Valley and Three Forks in the Lower Valley. The term ice gorging continues to be used to describe the Madison River winter ice-affected flooding.

Near the Town of Three Forks, the USGS maintained a river gage on the Madison River just downstream of the Climbing Arrow Road bridge between 1894 and 1950. Only four years of ice-affected stage were documented during the 9-year continuous record of 1942 to 1950, provided in **Table 1-5**. Recorded stages range from 7.67 to 10.48 feet. Interestingly the highest and lowest recorded stage occurred with a mean daily discharge of 1,200 cfs. The general trend, when ignoring the lowest stage, suggests that ice-affected stage at the USGS gage decreases with an increasing discharge. The highest open water stage recorded during this period was 5.89 feet and was associated with a discharge of 6,540 cfs.

Table 1-5: Ice Jam Flooding events on the Madison River

Date	Stage (ft)	Daily Discharge (cfs)
02/17/1942	9.98	1,400
01/18/1943	7.67	1,200
02/08/1948	10.48 ft	1,200
01/07/1950	7.84 ft	1,550

Additional flooding events associated with winter ice were documented in 1948, 1972, 1975, 1978, and c.a. 1985. The extent and nature of ice jamming during these events is unclear, other than that provided by anecdotal descriptions and photographs. For example, local resident Nellie Thomas, in an interview by Gail Schontzler (1997) of the Bozeman Daily Chronical, recalled that flooding in Old Town forced her family out of their home sometime around 1985. The 1972 flood overtopped the western levee downstream of I90 and flooded Old Town. A complete analysis of ice jam flooding can be found in **Section 3.14** and **Appendix I**.

Similar to the Madison River, peak flows on the Jefferson River and tributaries typically are a function of annual snowmelt and generally occur in the late spring or early summer. As an example, of the 80 years of peak flow records at USGS 06036650 Jefferson River near Three Forks, MT, all the annual peak flow events exceeding the 50% annual exceedance probability (8,490 cfs) occur in May or June. This dominance of spring/summer snowmelt on the annual peak flow record is reflected by other stream gages in the Jefferson River watershed. **Table 1-6** shows the highest recorded peak flow on the Jefferson at the USGS gage near Three Forks (Gage No. 06036650). Ice jam flooding does occasionally occur on the Jefferson River, but unlike the Madison River, the ice jam stages are not typically higher than the open water stages.

Table 1-6: Flood History on the Jefferson River near Three Forks

Jefferson River		
Station Name	Jefferson River near Three Forks	
Station Number	06036650	
Period of Peak Flow Data	1979–2017	
Number of Peak Flow Records	39	
Largest Recorded Events	Date	Peak Flow (cfs)
	6/12/2011	17,400
	6/9/1995	17,000
	6/11/1997	16,700
	5/24/1981	15,900
	6/24/1984	15,200

2. Hydrologic Analysis

Hydrologic analyses for the primary flooding sources of the Madison River and Jefferson River watersheds were documented in 2018 hydrologic reports by Baker (**Reference 7 and Reference 8**). Discharges for the 10-, 4-, 2-, 1, 0.2, and 1 percent 'plus'-annual-chance flood events were established for use in this hydraulic analysis. The hydrologic analyses provided recommended discharges that should be used in the hydraulic model. The watershed work maps from the hydrology reports are included in **Appendix D**.

A summary of discharges from the hydrologic reports is presented in **Table 2-1**. Due to flow splits (primarily in the floodplains throughout the study area), these discharges are <u>not</u> the final discharges used in the hydraulic analysis at many locations.

Table 2-1: Discharges Recommended from Hydrologic Analyses

Flooding Source and Location	Peak Discharges (cfs)					
	10-Percent	4-Percent	2-Percent	1-Percent	0.2-Percent	1-Percent 'plus
Madison River Confluence with Jefferson River (Node 100)	7,529	8,694	9,517	10,298	12,000	13,226
Madison River near Three Forks, MT (USGS Gage Station 06042500)	7,440	8,600	9,420	10,200	11,900	13,100
Jefferson River at Confluence with Madison River (Node 100)	15,088	17,896	19,900	21,803	26,108	25,219
Jefferson River near Three Forks, MT (USGS Gage Station 06036650)	15,000	17,800	19,800	21,700	26,000	25,100

Several flow splits occur in the floodplain around the City of Three Forks. Thus, the flow changes and values for each mapped flooding source as they were determined and applied in the hydraulic model is provided in **Section 3.3** and in the Flow Diagram Maps presented in **Appendix E**.

3. Hydraulic Analysis

The Three Forks study area contains a complex floodplain with a number of man-made features that require a thorough investigation to determine the risk of flooding to the community. The complicated flow paths and significant overbank flow features resulted in a hydraulic modeling approach that incorporates two-dimensional (2D) modeling techniques through a portion of the study area that was used to identify significant flow splits through the study area. The 2D model results were utilized to establish the 1D modeling framework that ultimately would be provided to the State, Community, and FEMA as the regulatory model that establishes the Base Flood Elevations and floodplain boundaries which will ultimately be used in the Flood Insurance Study and Flood

Insurance Rate Maps. However, prior to preparing the 1D regulatory model, a preliminary 1D model was developed to perform flow calculations (primarily through use of an extensive and complicated network of lateral weirs) that are used to define the flow values at flow change locations through the mainstem and split flow reaches. These calculated flow values are input as flow change locations for the various reaches within the regulatory model.

The following sections describe the methodology utilized for the Hydraulic analysis, specific information describing model set up and modeling parameters, and describe the worst-case scenario analyses that resulted in the final regulatory model prepared to support the Base Flood Elevations and floodplain boundaries.

3.1. Methodology and Hydraulic Model Setup

Hydraulic analysis for this study was performed using two different sets of models: one-dimensional (1D) and two-dimensional (2D). The 2D hydraulic models were created first in order to inform the creation of the 1D models, which are used for regulatory purposes.

2D hydraulic modeling was performed using HEC-RAS version 5.0.7 (**Reference 15**). Terrain data was created using the LiDAR data described in **Section 3.2.1,** with bathymetric survey data described in **Section 3.2.2** "burned in" to account for flow capacity beneath the water surface at the time of the LiDAR collection. A full description of the 2D models is provided in **Section 3.3.**

Informed by the 2D model, the 1D model was created using HEC-RAS version 4.1.0 (**Reference 16)**. This model version was used due to its superior handling of lateral weirs – many errors were identified in lateral weir calculations performed using HEC-RAS version 5.0.7, which could not be repaired. The USACE Hydrologic Engineering Center was contacted via email to discuss these errors, but no solution could be found other than the use of an earlier model version. Aside from the lateral weir issue, the calculation engines are similar and produce similar results.

All culverts, bridges, and inline structures were modeled in accordance with the HEC-RAS User's Manual, Version 5.0 (**Reference 18 and Reference 19**). In addition, standards listed in FEMA's Knowledge Sharing Site (KSS) (**Reference 20**) were followed to ensure the study meets FEMA's Guidance and Standards and accepted engineering practices. 2D modeling was performed using terrain data derived from LiDAR topographic data collection by Quantum Spatial in fall 2017 and documented in Madison River, Montana LiDAR Technical Data Report (**Reference 5**) and Jefferson River Watershed, Montana LiDAR Technical Data Report (**Reference 6**).

Detailed information on floodway modeling is in **Section 3.15** of this report. **Appendix B** contains the Hydraulic Work Maps and **Appendix E** contains the Flow Diagram Maps.

3.2. Field Survey and Topographic Information

Field survey and topographic information were collected using the methods and procedures outlined in FEMA's Guidelines and Standards for Flood Risk Analysis and Mapping. Specifically, FEMA's Data Capture Technical Reference (**Reference 21**), Guidance for Flood Risk Analysis and Mapping Data Capture - General (**Reference 22**), and Guidance for Flood Risk Analysis and Mapping Data Capture – Workflow Details (**Reference 23**) were adhered to.

3.2.1 LiDAR Collection

Terrain data was collected in October and November, 2017, for the entire study footprint area in the form of LiDAR points by Quantum Spatial (**Reference 5**). The LiDAR deliverables included digital elevation models (DEM) (3.0 ft resolution), 1.0 ft contours, and a report documentation among other items.

The LiDAR DEM (3.0 ft resolution) was the primary topographic source for the project and along with field survey data (bathymetric and structural surveys) was used to develop the HEC-RAS cross-sections.

3.2.2 Field Survey Collection

Bathymetric data collection was necessary to supplement the LiDAR data since the rivers are detailed study reaches which require a higher level of data input to achieve better modeling results. Detailed hydraulic analyses also require that all structures be included in the modeling unless it can be shown that the structure is not hydraulically significant to the model results. Therefore, field survey was collected.

Ground survey was collected for select riverine cross sections and hydraulic structures between October 2018 and January 2019 by Morrison-Maierle (**Reference 2**). Supplemental field survey at select locations was performed in May 2019. Additional ground survey for cross sections and hydraulic structures was collected between October and December 2017 (**Reference 3 and Reference 4**) Survey data was collected using GNSS RTK methods of survey. Additionally, a Trimble S6 Robotic Total Station was used to collect data at select locations where GPS signal could not be acquired. A SonarMite single beam echo sounder was used in conjunction with the GNSS RTK rover to map deeper portions of the flooding sources where wading was impractical. In total, for this study reach, 142 cross sections and 35 structures were surveyed. **Table 3-1** lists the number of cross-section and structure surveys that were completed for this study area.

The field survey data was presented in Montana State Plane 2500 coordinates, North American Datum of 1983 (NAD83-2011). Units are reported in International Feet. Elevations are referenced to the North American Vertical Datum of 1988 (NAVD88). Units are reported in U.S. Feet. GNSS-derived orthometric heights (elevations) were computed using Geoid 12B.

In addition, photographs and sketches of each hydraulic structure were taken to assist with the creation of the hydraulic model cross-section geometries. These photographs are included in **Appendix F** of this report. All surveyed hydraulic cross sections and structures were incorporated into the hydraulic model.

Table 3-1: Field Survey Collection Summary

Flooding Source	Number of Hydraulic Structures	Number of Cross Sections
Three Forks – Jefferson River and Madison River	35	142

3.3. 2D Modeling

Hydraulic modeling of the Jefferson River and Madison River was initially performed using HEC-RAS 2D version 5.0.7. A total of six scenarios were modeled to represent a 'with levee' condition and five 'without levee' conditions, as discussed in **Section 3.13**. Since the 2D model scenarios were used to inform the 1D analyses, 2D analyses were only performed for the 1-percent annual chance flood events on the Madison and Jefferson Rivers, as presented in **Section 2**.

The 2D model domain and boundary conditions remained unchanged across all models and encompassed both the Jefferson and Madison Rivers. The model domain extended from approximately 1.3 river miles downstream of the Jefferson-Madison confluence to approximately 15.1 river miles upstream of the confluence on the Jefferson River and 11.8 miles upstream of the confluence on the Madison River. Lateral extents of the model domain were extended to encompass the model solution, which extended to higher ground outside the limits of floodplain flows.

Breaklines were used to force the placement of cell faces and increase cell density at controlling high ground (e.g. roads, levees, embankments) and at distinct grade breaks (e.g. channel banks). Computational point spacing varied from 10 feet to 50 feet. Mesh quality was reviewed, and computation points adjusted to satisfy mesh quality guidance.

Each mesh was associated with its respective terrain layer. The existing conditions LiDAR and bathymetric survey data, discussed in **Section 3.2**, were used to create a 'with levee' DEM (3.0 ft resolution). Tools available in GeoHECRAS (**Reference 17**) were used to 'burn' bathymetric survey into the LiDAR DEM. Manual adjustments were performed in GIS to smooth transitions of individual channels at bifurcation and confluences. For each 'without levee' scenario, the 'with levee' terrain was modified using GIS methods, where the levee terrain is replaced with terrain data representing the respective 'without levee' condition. Additionally, the 'without levee' scenario incorporated terrain data representing the adjacent toe of embankment.

All meshes utilized the same roughness (Manning's n) layer. Manning's n values are described in **Section 3.7** and presented in **Table 3-7**.

Hydraulic structures were incorporated into the 2D model scenarios by representing bridges as openings in the terrain and approach slopes and abutments as represented in the terrain. Piers were not modeled because they were evaluated and determined to have limited hydraulic significance for the high (1% annual chance) flows modeled. Culverts were modeled as described in **Section 3.9**. Based on limitations in modeling capabilities, culvert invert elevations must be equivalent to or higher than the minimum elevation of their associated 2D cell. Attempts to locally adjust terrain data at culvert inlets and outlets to match surveyed culvert invert elevations were unsuccessful. The HEC conversion of terrain TIFF to HDF files did not, in all cases, capture the minimum elevation represented in the modified terrain TIFF. As such, a few culverts had modeled inverts above the surveyed invert elevation. The minimum controlling cell elevation and surveyed culvert slope were used to establish invert elevations. However, review of model results indicates that model results without elevation adjustments yields reasonable results.

Upstream boundary conditions were assigned as flow hydrographs having constant discharges of 10,200 cfs on the Madison River and 21,700 cfs on the Jefferson River. Discharges were held constant over the entire model simulation time to represent steady state conditions. The downstream boundary condition was assigned a normal depth friction slope of 0.04, which is consistent with channel slopes at downstream extents of modeled reach. The 2D model boundary conditions are included in **Table 3-6**.

The computational parameters are presented in **Table 3-2**. A simulation time of 36 hours was selected for all scenarios and the solution at the final time step were used to evaluate flow distribution across the model domain. The 36-hour simulation time was established to ensure relatively steady state conditions; water surface elevation and discharge at critical locations within the model varied by less than 0.1 feet or 1% of discharge computed for the prior output interval.

Table 3-2: HEC-RAS 2D Computational Parameters

Computational Parameter	Value
Simulation Time	36 hours
Computation Interval	1 second [Jefferson without East Levee Scenario: Controlled by Courant Condition (assigned range limit 3 to 0.5 seconds)]
Output Interval	30 minutes
Theta	1.0
Theta Warmup	1.0
Water Surface Tolerance	0.01
Volume Tolerance	0.01
Maximum Iterations	20
Equation Set	Diffusion Wave

3.4. Split Flow Analysis

2D modeling results indicated that it would be necessary to model flow splits off of the Jefferson River to properly represent 1% annual chance flow conditions within the study reach in a 1D modelling analysis. Three flow splits were incorporated into the 1D model to accurately represent the split flow paths. A brief description of each of these split flows, as well as the modeling plan where flow split calculations were performed, is provided in **Table 3-3**.

Table 3-3: Split Flow Descriptions

Split Flow Name	Splits from	Model Project/Plan	Stream Length (miles)
Frontage Split	Jefferson River	Three Forks/Flow Calc_ThreeForks_w_levee	4.7
FR Overflow	Frontage Split	Three Forks/Flow Calc_ThreeForks_w_levee	1.2
Jeff RR Split	Jefferson River	Three Forks/Flow Calc_ThreeForks_w_levee	0.8

Lateral weir calculations were used to represent the flow splits in the 1D model. Lateral weir geometry was extracted from the LiDAR data in the locations where the 2D model indicated that flow would split from the main reach. Lateral weir coefficients were selected to best represent the flow distribution under the 1%-annual-chance event in the 2D model – essentially, the 1D model was calibrated to the 2D model.

Table 3-4 describes the lateral weirs incorporated into the model along with the associated weir coefficient for the "Flow Calc_ThreeForks_w_levee" plan. Generally, weir coefficients fell within the acceptable range recommended by HEC in the document "HEC-RAS 5.0 2D Modeling User's Manual".

The flow splits that go from the Frontage Split back the Jefferson River and to the FR Overflow travel through culverts under Frontage Road. These culverts are modeled as a part of the lateral structures. The culverts are influenced to varying degrees by the tailwater, depending on their location. The tailwater on the Jefferson River and the FR Overflow tends to limit the magnitude of flow that goes through these culverts.

Some of the flow calculation model runs produce the HEC-RAS warning, "Flow Optimization Failed to Converge" under certain profiles. This is a common warning produced by HEC-RAS models with multiple optimized lateral weirs. In these cases, the flow calculations were closely examined to ensure that the model was stable and produced reasonable results that were near convergence.

The network of split flows changed the magnitude of peak discharges for the Madison River flooding sources that were incorporated into the regulatory analysis because the controlling flood on the Madison River is an Ice Jam event (for more discussion of ice jam affected flooding, see **Section 3.14**). The discharge values on the Jefferson River and the splits are also impacted by the split flow analysis. Because these flow splits remove flows from the mainstem, the discharge values published in the hydrologic studies were modified along the study reach to account for the impacts of the split flows.

However, a valley-wide flow balance confirms that published flow values are implemented through the sum of mainstem and split flow paths. The Cross Section Discharge and Elevation Table in **Appendix H** provides the discharge values at cross sections for each flow split and mainstem reach. The flow diagram that illustrates the splits is provided in **Appendix E.**

Table 3-4: Lateral Weir Coefficients

Lateral Weir Identifier	"Parent" Flooding Source	Receiving Flooding Source	Description	Weir Coefficient
53714	**Jefferson River**	**Frontage Split**	Flow splits off of the Jefferson River on the right overbank to form Frontage Split.	0.30
52087	**Jefferson River**	**Frontage Split**	Continuation of lateral weir 53714	0.30
19577	**Jefferson River**	**Madison River**	Flow moves from the Jefferson to the Madison through a bridge under the railroad embankment	0.575
8717	**Jefferson River**	**Jeff RR Split**	Flow splits over an embankment on the left overbank of the Jefferson River to form Jefferson Split	0.35
18919	**Frontage Split**	**Jefferson River**	Flow from two culverts under Frontage road returns to the Jefferson River	2.6
18369	**Frontage Split**	**FR Overflow**	Flow from three culverts under Frontage Road leaves to form FR Overflow	2.6
11973	**Frontage Split**	**FR Overflow**	Flow overtops high ground on left overbank of Frontage Split to join FR Overflow	0.31
7789	**Frontage Split**	**Jefferson River**	Flow overtops high Ground on right overbank of Frontage Split to rejoin the Jefferson River	0.25
4029	**Frontage Split**	**Madison River**	Flow moves through underpass to join Madison River downstream of I-90	0.50
1885	**Frontage Split**	**Madison River**	Flow moves over non-certified levee on the left overbank to join Madison River	2.6
2347	**Jeff RR Split**	**Jefferson River**	Flow moves through opening under railroad embankment to rejoin the Jefferson River	0.10

3.5. Profile Baseline

The centerlines for all flooding sources were used to define the Profile Baselines and river stationing as the stream distance. The stream stationing for all modeled reaches reference the stream distance in feet above a certain point. **Table 3-5** lists all modeled streams and their stationing references. Additional information on key features along each profile baseline can be found in tables in **Appendix H**.

Table 3-5: Summary of Station References

Flooding Source	Station Reference
Jefferson River	Feet above limit of study
Madison River	Feet above confluence with Jefferson River
Frontage Split	Feet above confluence with Madison River
FR Overflow	Feet above limit of study
Jeff RR Split	Feet above confluence Jefferson River

3.6. Boundary Conditions

A review of the hydrologic conditions at the confluence of the Jefferson and Madison Rivers indicates these rivers have coincident peaks. Thus, the downstream boundary condition for the Madison River is the water surface elevation of the Jefferson River under the associated flood profile. **Table 3-6** summarizes the boundary conditions used in the analysis.

Table 3-6: Boundary Conditions

Flooding Source	Boundary Condition
Jefferson River (2D)	Upstream: 21,700 cfs Downstream: Normal Depth = 0.04
Madison River (2D)	Upstream: 10,200 cfs
Jefferson River	Downstream: Normal Depth = 0.0005
Madison River	Junction with Jefferson River
Frontage Split	Junction with Madison River
FR Overflow	Junction with Jefferson River
Jeff RR Split	Junction with Jefferson River

3.7. Manning's Roughness Coefficients

Manning's roughness coefficients (Manning's n values) were determined based on interpretation of aerial imagery and photographs provided by the Morrison-Maierle survey (**Reference 2, Reference 3, and Reference 4**). Fifteen land cover designations were identified within the study reach with Manning's 'n' values ranging from 0.035 (stream channel) to 0.07 (Riparian trees and brush); a value of 1.0 was assigned to building footprints in the 2D model only (**Table 3-7**). 1D study area Manning's n values were manually established based on observation of the land cover type and extent of the coverage. For the 2D study areas, land use was manually digitized based on interpretation of aerial photo imagery and assigned a land use class with an associated Manning's 'n' value. 2D analyses use the roughness grid for calculations at the grid scale.

Table 3-7: Manning's n Values used in Hydraulic Model

Annual Exceedance Probability	Range of Manning's n Values
Channel	0.035
Overbanks - Agriculture	0.04
Overbanks - Building	1.0
Overbanks - Developed	0.06
Overbanks - Dirt and Grassland	0.035
Overbanks - Ditch	0.035
Overbanks - Grassland	0.045
Overbanks - Grassland and Bushes	0.06
Overbanks - Pasture Grass	0.04
Overbanks - Pond/Water	0.035
Overbanks - Riparian Grass	0.045
Overbanks - Riparian grass/brush	0.06
Overbanks - Riparian trees/brush	0.07
Overbanks - Roadway	0.016
Overbanks - Trees	0.07

3.8. Development of Cross-Sectional Geometries

Cross sectional geometries were established based on topographic information derived from the 2017 LiDAR collect and the field survey (**Section Error! Reference source not found.**). Cross sectional geometries were extracted from the LiDAR sourced DEMs using GeoHECRAS (**Reference 17**). At locations where cross section survey was collected, the survey data was conflated into the cross section at the appropriate location using manual methods.

At cross section locations along the primary flooding sources where survey data was not collected, bathymetric cross section geometry was either interpolated between adjacent surveyed cross sections or typical channel bathymetric characteristics were burned into the DEM surface and cross section geometry was extracted from this modified DEM. The same DEM's were used for 1D cross section extraction and the 2D modelling (from the 'with levee' scenario).

The 'without levee' scenario cross section geometries were unchanged. Rather, ineffective areas originally assigned to prohibit conveyance on bankward side of levee or embankment (**Section 3.10**) were removed or adjusted to allow conveyance bankward of the levee/embankment.

The cross sectional geometries for cross sections on the secondary (split flow) flooding sources where survey was not collected were determined using the LiDAR terrain data only. Given that these flooding sources contained no water or minimal water depth when the LiDAR was collected (e.g. late fall low flow conditions), bathymetric or field survey data would not improve the modeling geometries. Therefore, survey was not collected or used in the model for these flooding sources.

Cross section locations were set using established engineering practice and guidance provided in the HEC-RAS Hydraulic Reference Manual.

Contraction and expansion coefficients were generally set as recommended in the HEC-RAS Hydraulic Reference Manual (0.1 and 0.3 in areas of gradual transition, and 0.3 and 0.5 at typical bridge sections).

Bank stations were placed at the boundary between the stream channel and the overbank area. When possible, this location represented a topographic inflection point which divides the stream from the overbank. Due to the unique hydrologic and hydraulic attributes of the Jefferson and Madison Rivers and modeled split flows, bank stations vary and may be at a higher elevation than most typical riverine studies and may encompass well vegetated islands. FR Overflow, specifically, represented a variety of possible flow paths for a scenario in which Frontage Road was breached by floodwaters. Bank Stations on this reach were placed to represent the most likely flow path, but no ineffective is included on this reach as there are multiple channels which could convey flow.

Channel thalweg elevations occasionally created seemingly uphill ground surface gradients between cross sections in localized areas. The uphill gradient is typically not significant and is likely caused by local sediment scour and deposition or is representative of a pool-riffle morphology.

Photographs of select cross sections (adjacent to hydraulic structures) are provided in **Appendix F.** Cross section numbering is based on the HEC-RAS river stations and not the river station the cross section was assigned when the field survey was collected. The “Surveyed Structure Stationing Key” table in **Appendix F** provides a cross walk between the HEC-RAS river stations and the survey data. In addition, a “Structures without Photographs” table is included in **Appendix F** to list the structures that do not have associated photographs. The modeled cross section geometries are provided in **Appendix G.**

3.9. Hydraulic Structures

Hydraulic structures were represented in HEC-RAS using established engineering practice and guidance provided in the HEC-RAS Hydraulic Reference Manual. Field survey data were available for 35 structures in the study area. Six bridges and two culverts were modeled on the Jefferson River. One bridge was modeled on the Jefferson River within the modeled lateral weir representing the railroad embankment. Three culverts were modeled on the Frontage Split within the modeled lateral weir representing Montana Highway 2. Nine bridges were modeled on the Madison River. Remaining hydraulic structures that were surveyed were either included in the 2D model or were located beyond the inundation limits or cross section extents. A summary of modeled structures is provided in the “Summary of Modeled Hydraulic Structures” table in **Appendix H**.

Survey data were utilized to provide structure geometries. The photographs, sketches, and spatial data were all referenced to most reasonably and accurately model the geometry of each individual hydraulic structure.

Appropriate low flow and high flow structure modeling approaches were implemented in accordance with guidance provided in the HEC-RAS Hydraulic Reference Manual.

Photographs of hydraulic structures are provided in **Appendix F**. Structure and cross section geometries are provided in **Appendix G**.

3.10. Non-Conveyance/Blocked Obstruction Areas

Ineffective areas and blocked obstructions were used in the model to restrict flows to areas of cross sections capable of actively conveying flow. Ineffective flow areas were used to model several different hydraulic scenarios:

1. In the vicinity of hydraulic structures, ineffective areas are used at locations that would not actively convey flow due to being blocked by the abutments or the approach to the structure itself. These ineffective areas were placed in accordance with structure modeling guidance provided in the HEC-RAS Hydraulic Reference Manual.

2. For hydraulically disconnected regions, ineffective areas were added to the model to account for the fact that flow would not be actively conveyed in these areas. This includes isolating areas that would be protected by embankments or levees.

3. In overbank areas where flow during flooding events would be minor or insignificant, ineffective areas were used to ensure that accurate hydraulic calculations were taking place in the active, more significant flowpaths. These areas tend to be at locations where flow cannot access overbank areas, such as locations where flow to lower overbank areas are blocked by high ground or an embankment near to the bank station.

4. Areas of backwater were modeled as ineffective flow.

5. Areas where the flow would be predominately lateral to the primary direction of flow were modeled as ineffective flow areas. One example of this would be at a cross section where a lateral incoming ditch was picked up along the cross section from the terrain data. These areas of lateral flow would not convey flow effectively in the primary flow direction during a flooding event.

Blocked obstructions were also used in the model. These blocked obstructions were primarily used to represent buildings or structures that would block conveyance at (or in close proximity to) a cross section.

All ineffective areas and blocked obstructions were placed in accordance with sound engineering judgment and guidance from the HEC-RAS Hydraulic Reference Manual. In total, 226 cross sections contain either ineffective flow, blocked obstructions, or both. A summary of cross sections with ineffective areas or blocked obstruction, along with reason for the placement of ineffective or blocked areas, is contained in the "Explanation of Ineffective and Blocked Flows" table in **Appendix H.**

3.11. Model Results and Mapping

The models appear to produce reasonable results throughout the study reach. The floodplain is broad in many areas, with numerous primary and secondary flowpaths through the study reach. This is expected in these locations and reasonable given the underlying terrain and because the channel is undersized relative to the magnitude of flow during the low recurrence interval, higher magnitude flow events evaluated in this study.

The resultant floodplains were exported from the model and smoothed and minimally refined using automated processes. During the floodplain mapping phase of the project, the initial results containing "raw" floodplain output were refined as described in **Section 4** and included in **Appendix B**.

3.12. Letter of Map Revision and Existing Study Data Incorporation

No LOMRs or any other existing studies were included in this analysis.

3.13. Multiple/Worst Case Scenario Analysis

Multiple non-certified levees and non-levee embankments exist within the study area, on both the Jefferson River and the Madison River. Each of these structures was studied in order to perform a multiple/worst case scenario analysis. Details on each of these analyses is provided below.

3.13.1 Madison Levee East

Madison Levee East is a non-certified levee structure on the right side of the Madison River that begins upstream of the study boundary, and continues to a short distance downstream of Interstate 90 – a distance of over 8 miles. It is significant structure, ranging from around 8 to 10 feet in height above the surrounding terrain. If this non-certified levee were to fail, flow would move to east of the Madison River. At some locations, the flow would be captured by a designed ditch on the landward side of the levee, or it may expand further to the east in the valley.

For this structure, with- and without- levee analysis was performed for the entirety of the levee reach. The with-levee analysis uses ineffective flow areas at the top of the levee structure in the model cross sectional geometry. This analysis can be found in the model plan titled "Regulatory_ThreeForks_w_levee". The without-levee analysis allows flow to be effective in the ditch on the landward side of the levee, and can be found in the model plan "Regulatory_ThreeForks_wo_levee". Water surface elevations for the without levee analysis are typically 0 to 0.9 feet lower, and should be used to map flood hazards on the landward side of the levee. On the river side of the levee, the with-levee elevations should be used. Failure of this non-certified levee is not likely to produce flow that will follow a separate flow path from the Madison River or the adjacent ditch; therefore, no separate flow calculations are necessary.

3.13.2 Madison Levee West

The Madison Levee west is a non-certified levee on the left side of the Madison River upstream of Interstate 90, stretching from the Interstate 90 highway embankment to the bluffs on the left side of the Madison River approximately 1500 feet upstream of Interstate 90. The Frontage Split model reach, which splits off from the Jefferson River and goes through the City of Three Forks, crosses over this non-certified levee before entering the Madison River.

Both the 1D and 2D analyses indicate that during the 1%-annual-chance event for both the Jefferson River and the Madison River, flow moves across the top of this non-certified levee from west to east (into the Madison River). Therefore, the worst-case scenario for Frontage Split (as well as the Jefferson River) occurs when the levee remains in place during a flood event – water backs up against the levee before overtopping and joining the Madison. Flow calculations for this scenario are provided in the model plan titled “Flow Calc_ThreeForks_w_levee”. Regulatory flood elevations for this scenario are provided in the model plan titled “Regulatory_ThreeForks_w_levee”.

The worst-case scenario for the Madison River involves the failure of this non-certified levee. The failure of this levee during the 1%-annual-chance event would mean that more flow comes through the Frontage Split into the Madison River, instead of returning to the Jefferson. Flows for this worst-case scenario are calculated in the model plan titled ““Flow Calc_ThreeForks_wo_Mad_levee_west”. However, no regulatory flood elevations occur as a result of this scenario, because the worst-case scenario flood on the Madison occurs during an ice-jam event, which is not concurrent with flooding on the Jefferson or Frontage Split. (see **Section 3.14** for details on ice jam flooding on the Madison).

3.13.3 Jefferson Railroad - Upstream

During the 1%-annual-chance-event, the railroad south of the City of Three Forks acts as a non-levee embankment that will influence flows on the Jefferson River. This flow split would move over a broad, flat area, crisscrossed with small agricultural berms and other impediments that make the flow path highly unpredictable.

For this non-levee embankment, the worst case scenario on the Jefferson River occurs when the embankment remains in place during a flood event. Water surface elevations for this scenario are calculated in the 1D model plan titled “Regulatory_ThreeForks_w_levee”. No flows are deducted from the Jefferson River in the 1D model in this area.

The worst case scenario for the east side of this non-levee embankment occurs when the embankment fails. Due to the lateral movement and unpredictable flows in this area, it is most reasonable to map this area using results from the 2D model with this non-levee embankment removed.

3.13.4 Jefferson Railroad – Downstream

Downstream of I-90, a railroad embankment separates the Jefferson and Madison Rivers until just before their confluence. If this non-levee embankment were to fail, flow would move from west to east, from the slightly higher Jefferson River to the slightly lower Madison River. Therefore, the worst case scenario for the Jefferson River in this area involves the embankment remaining in place, keeping the flow on the Jefferson side. Water surface elevations for this scenario are calculated in the 1D model plan "Regulatory_ThreeForks_w_levee".

The worst case scenario for the Madison River in this area involves the embankment failing during a flood event, such that flow would move freely from the Jefferson into the Madison. However, no regulatory flood elevations occur as a result of this scenario, because the worst-case scenario flood on the Madison occurs during an ice-jam event, which is not concurrent with flooding on the Jefferson or Frontage Split. (see Section 3.14 for details on ice jam flooding on the Madison).

3.13.5 Frontage Road

Frontage Road is an elevated roadway that runs perpendicular to the Jefferson River and parallel to Frontage Split. If this non-levee embankment were to fail, flow would move northward from the Frontage Split into the Jefferson River and the Frontage Road Overflow. Therefore, the worst case scenario for the Jefferson River downstream of Frontage Road and for Frontage Road Overflow involves this embankment failing. Flows for this scenario are calculated in the 1D model plan "Flow Calc_ThreeForks_wo_Frontage Road" and water surface elevations for this scenario are calculated in the 1D model plan "Regulatory_ThreeForks_w_levee".

The worst case scenario for Frontage Split in this area involves the Frontage Road embankment remaining in place, which would allow flow to continue along Frontage Split through the City of Three Forks. Flows for this scenario are calculated in the 1D model plan "Flow Calc_ThreeForks_w_levee" and water surface elevations for this scenario are calculated in the 1D model plan "Regulatory_ThreeForks_w_levee".

3.14. Ice Jam Analysis

An ice jam analysis was performed to support this study. A memo detailing the ice jam analysis is provided in **Appendix I**. Evaluations of ice jam data on the Madison and Jefferson Rivers determined that ice jams on the Jefferson do not yield a flood elevation in excess of open water conditions, so the ice jam analysis was limited to the Madison River reach. Guidance for Flood Risk Analysis and Mapping – Ice-Jam Analyses and Mapping (**Reference 27**) was followed for this analysis.

Historical ice-affected flooding on the Madison River near Three Forks dates as far back as 1867. Unfortunately, most of the documentation is qualitative or anecdotal. The historical stage-discharge record is limited to a consecutive nine-year period with four years having a peak annual stage that was ice-affected (USGS at Gage No. 06042500). Ice-affected flooding on the Madison River has historically occurred during the winter months, between December and March. Flooding is the result of winter ice gorging, a process by which the channel becomes choked by the development of frazil ice and anchor ice over an extended period of extreme cold weather. Ice gorging typically occurs over long river runs; in excess of 10 miles. Ice gorging can either reduce conveyance area of the channel(s) and floodplains by the local development of ice (identified in this analysis as ice gorging), or it can be transported downstream and subsequently accumulate on fixed ice cover or at hydraulic constrictions (identified in this analysis as freezeup jams).

Effective mapping of the Madison River is based on indirect methods of ice jam modeling performed by Van Mullem in 2004 (**Reference 28**). This study attempted to update the ice jam modeling using HEC-RAS for the entire Madison River reach. However, a reasonable ice jam model could not be developed and there is insufficient support for the methods and assumptions used to develop the Van Mullem model. It was determined that the equations used to model breakup ice jams in HEC-RAS are not suited to modeling the development and distribution of ice gorging or freezeup jam conditions on the Madison River.

Direct methods were used to develop an adjusted ice-affected rating curve at the Madison River gage station using the nine years of historical gage data collected between 1942 and 1950. The direct analysis clearly indicates that the ice-affected stage can be significantly higher that open water stages on the Madison River. Current FEMA guidance indicates that Mapping Partners will usually not be required to address freezeup-type jams when performing enhanced studies, other than when possible exceptions exist (**Reference 27**). The direct analysis indicates that the Madison River at Three Forks is such an exception, because the ice jam occurrence during low magnitude flows can yield water surface elevations substantially higher than open water 1% annual chance conditions.

However, the period of record at the gage does not satisfy the requirements that make the direct analysis the preferred approach. Given unreasonable profiles and ice thicknesses modeled by the indirect analysis, and lack of confidence in the model results, the direct analysis is the preferred approach for this study. Further detailed discussion of reasoning and defense for this determination are presented in **Appendix I**.

Other nearby gages were reviewed in order to identify possible trends in ice-affected stage (geographically and with extended periods of record) that would support use of the direct analysis of the Madison River gage at Three Forks. The comparative analysis of local gages determined that the incidence and severity of ice jam flooding in the region is highly variable and dependent on local river characteristics. This finding is in agreement with the overall understanding of ice-affected flooding in general. However, historical documentation indicates that ice-affected flooding on the Madison River is unique in its general characteristics and severity.

To establish the ice-affected profiles and flood mapping on the Madison River, the ice-affected surcharge was applied to the open water profile modeled in HEC-RAS (**Table 3-8**). The ice-affected surcharges were determined from the adjusted rating curve developed at the gage station. Surcharges were applied through the entire Madison River study reach. Further detailed discussion of reasoning and defense for this approach are presented in **Appendix I**.

Table 3-8: Madison River Ice-Affected Surcharges

Annual Exceedance Probability	Ice-Affected Surcharge (ft)
10-Percent	2.8
4-Percent	3.9
2-Percent	4.2
1-Percent	4.4
0.2-Percent	4.7
1-Percent 'plus'	4.4

3.15. Floodway Analysis

A floodway analysis was performed for all study reaches, including split flow reaches. Floodway was determined using the equal conveyance reduction method. Per state of Montana guidelines, the maximum allowable surcharge at any given cross section is 0.50 feet. The floodway encroachment stations were revised until this requirement was met.

Several notes on the equal conveyance reduction floodways:

- The encroachment stations are set using the HEC-RAS hydraulic modeling program (Mode 4), encroaching on the overbanks on each side of the channel by reducing the conveyance equally on both sides until the target surcharge (0.50 feet) is met.
- When HEC-RAS sets the encroachment stations after the first floodway modeling run, there are frequently surcharges greater than the maximum allowable at many cross sections. Encroachments determined using Mode 4 are copied over to Mode 1. As required, stations are adjusted on a cross section-by-cross section basis until the maximum allowable surcharge is not exceeded at any cross section.
- It is generally not possible for the surcharge to be exactly 0.50 feet at all locations. The surcharge is brought as close to the maximum allowable height at each cross section without going over.
- Negative surcharges are occasionally calculated in HEC-RAS. Efforts were made to change the encroachment stationing to remove the negative surcharges.

- At some areas where cross sections are close together, the equal conveyance reduction method produces a floodway that is unreasonable due to inconsistent floodway widths between cross sections. The floodway is smoothed by manually moving encroachment stations in the model.

- Because the encroachments are not allowed into the channels of flooding sources, floodways sometimes appear to be unbalanced. However, this is appropriate: if the channel is on the far-left side of the floodplain, for example, the left side cannot be further encroached and all encroaching is done on the right side of the floodplain.

Establishing floodway on the Madison River required an alternate approach than is typical of other reaches modeled for open water conditions. Regulatory profiles and floodplain extents for the Madison River were developed using open water conditions plus an ice-affected surcharge. Using the open water model to develop floodways may actually produce an unreasonably narrow floodway. Under ice-affected conditions the conveyance area will be significantly reduced by ice gorging. Despite a lower winter discharge, this reduction in conveyance could further exacerbate a rise in stage associated with reduced conveyance by encroachment.

To approximate conveyance area associated with ice-affected conditions, an analogous model was developed for the Madison River using increased discharges. Discharges were iteratively selected to approximate the ice-affected flood profile along the entire model each. This approximates the relative conveyance area necessary to achieve the regulatory water surface elevation, though it is likely conservative for ice-affected flooding conditions. A floodway analysis was then performed on this analogous model as described above. The resulting encroachment stations were then assigned to the open water model using the 1-percent annual chance discharge to check that floodway surcharges do not exceed the established requirement of 0.50 feet. The resulting Regulatory base flood elevations were assigned the same ice-affected surcharge (4.4 feet) as the open water model for tabulation of FWDTs (**Section 5.2**). Footnotes are included in the FWDT to indicate that the Regulatory BFE's are the ice affected Base Flood Elevations and the With and Without Floodway BFE's are based on open water flow calculations only.

In the area of the Jefferson River, Frontage Split, and Frontage Road Overflow, the primary flow paths (Jefferson River, Frontage Road Overflow, and the upper portions only of Frontage Split) can carry the entire base flood flow without increasing flood heights more than the maximum allowable surcharge. Therefore, floodways are only required on these flow paths. No floodway is required on Frontage Split downstream of Frontage Road Overflow. Therefore, no floodway was required in this area.

Administrative floodways were considered along Frontage Split to maintain existing flow distribution. However, because the flooding on the Jefferson River and the Frontage Road Overflow is controlled by the "worst case scenario" of the failure of the Frontage Road embankment, there is no potential project in along the Frontage Split downstream of Frontage Road Overflow that could increase the flows on the Jefferson River or the Frontage Road Overflow above what they already are. Therefore, an administrative floodway is not necessary or appropriate in this area.

3.16. Calibration - Verification

Two USGS gages are located within the study area – USGS Gage No. 06042500 (Madison River near Three Forks, MT), and USGS Gage No. 06036650 (Jefferson River near Three Forks, MT). Each gage was investigated to determine suitability for calibration or verification of hydraulic analysis results.

The gage on the Madison River (06042500) has 16 years of annual peak data available from 1894-1896, 1929-1932, and from 1942-1950. This gage was used in the ice jam analysis (described in **Section 3.14**) due to its record of ice jam events between 1942-1950. However, the gage was discontinued in 1950, and removed some time after. The gage datum listed by USGS is clearly incorrect, and none of the reference monuments were found by surveyors in the field in order to establish a correct datum. Therefore, no water surface elevation model calibration could be performed using this gage.

However, the gage on the Jefferson River (06036650) is still active and useful for model calibration. The gage has 39 years of annual peak data available, from 1979-2017. Surveyors in the field were able to collect elevation data for three known reference monuments in the field, which were used to establish a corrected datum for the gage.

Two annual peak events on the Jefferson River were selected for calibration purposes: 2011 and 2017. These events were chosen for their relative recency as well as for their higher magnitude of flow – the 2011 event produced the highest discharge in the gage's period of record (17,400 cfs), while the 2017 event produced a discharge of 10,300 cfs. With the corrected datum and the stage information from the gage data, reliable water surface elevations for each of these events was computed. A calibration run of the 2D model was performed using the 2011 discharge, whereas both events were used to calibrate the 1D model. Manning's n values were adjusted in order for the model results to match the elevations for each event. Calibration was performed to within less than a tenth of a foot for each event. Calibration data is provided in **Table 3-9**.

Table 3-9: Calibration Data

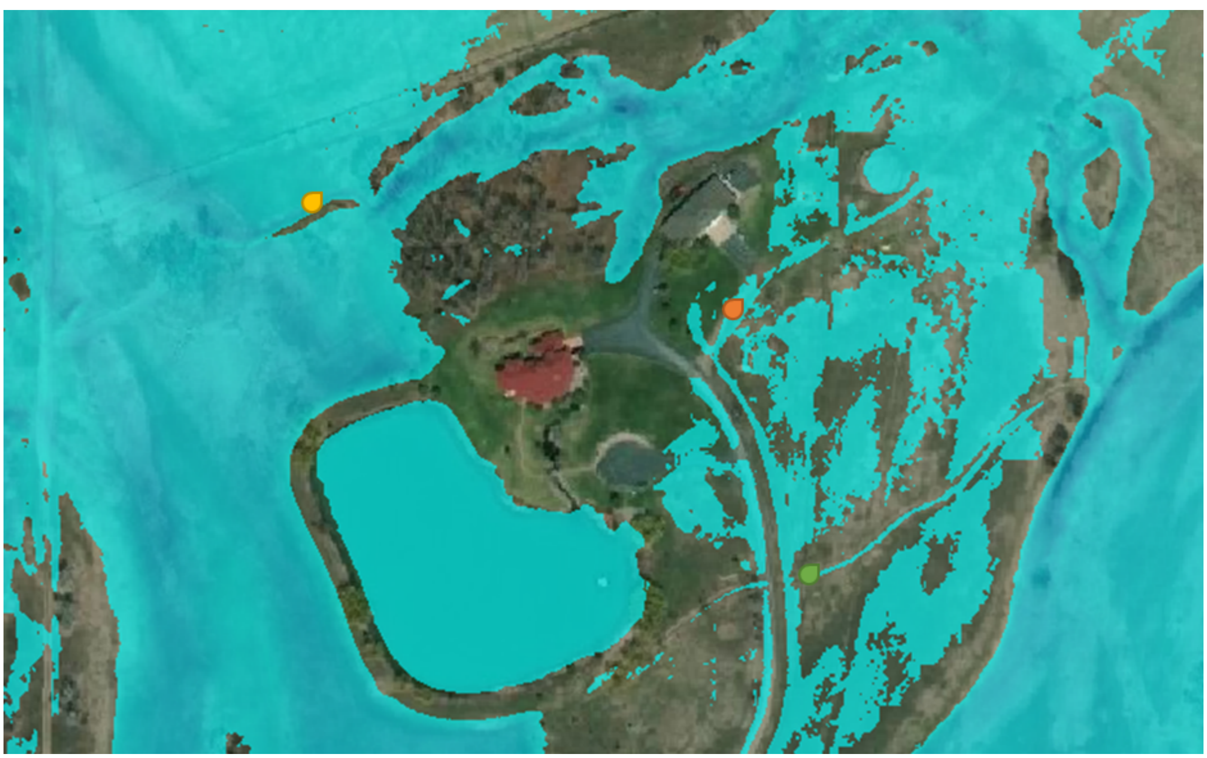
Annual Peak Year	Gage Discharge (cfs)	Gage Stage (ft)	Gage Water Surface Elevation (ft NAVD)	Calibrated Model WSEL (ft NAVD)
2D Model				
2011	17,400	9.38	4088.86	4088.92
1D Model				
2011	17,400	9.38	4088.86	4088.95
2017	10,300	7.68	4087.16	4087.13

The 2D model was only calibrated to the 2011 event because it was the greater of the two events and was most closely representative of the 1-percent annual chance flood event. To achieve the reported 2011 discharge at the gage site an inflow boundary condition of 17,845 cfs was assigned to the Jefferson River. A proportionately equivalent discharge, relative to the 1-percent annual chance flood event, was assigned to the inflow boundary of the Madison River. Accounting for split flow losses the 2D modeled discharge at the gage was 17,305 cfs; within 0.6% of the reported peak annual discharge of 17,400 cfs.

To further validate the 2D model calibration, oblique aerial imagery of select residences captured during the 2011 flood along the Jefferson River were compared against modeled flood inundation. **Figure 3-** through **Figure 3-** between 2011 flooding and modeled flood extents. Colored symbols are used to correlate relative locations between images.

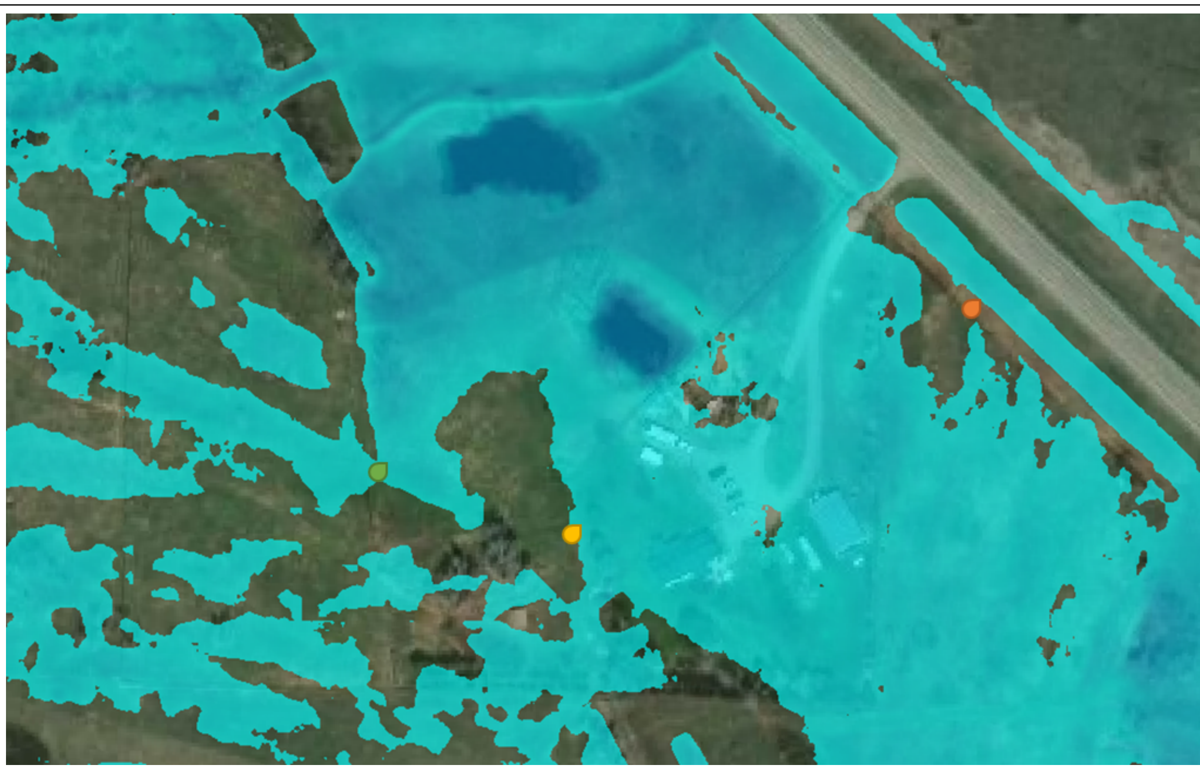
Overall, this calibration effort indicates that the models are performing reliably and producing results that can be expected to accurately represent real-world flooding events.

Figure 3-1: North of Frontage Road - 2011 Flood Imagery vs 2D Model Calibration



Approximate Location: 1438161, 608294 (NAD83 2011 Montana State Plane)

Figure 3-2: South of Frontage Road - 2011 Flood Imagery vs 2D Model Calibration

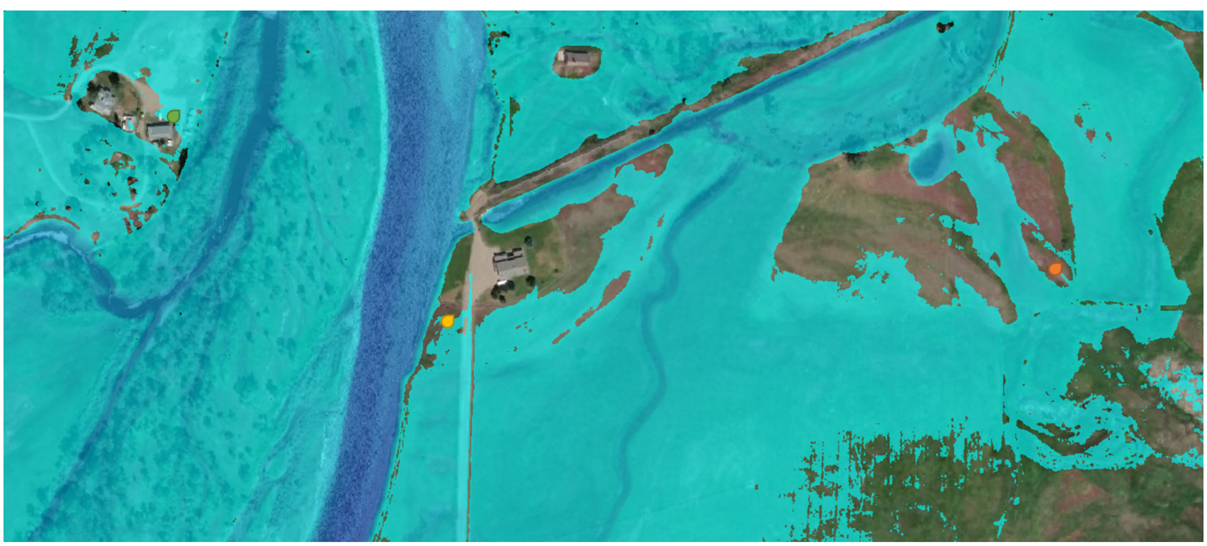


Approximate Location: 1436037, 606175 (NAD83 2011 Montana State Plane)

Figure 3-3: Between Three Forks and Willow Creek - 2011 Flood Imagery vs 2D Model Calibration

Approximate Location: 1430564, 600273 (NAD83 2011 Montana State Plane)

Figure 3-4: North of Willow Creek - 2011 Flood Imagery vs 2D Model Calibration



Approximate Location: 1419846, 586529 (NAD83 2011 Montana State Plane)

4. Floodplain Mapping

FEMA's KSS and many of FEMA's technical guidance documents were consulted to ensure the mapping meets mandatory requirements necessary to map the results of this study on Gallatin County's FIRM panels in the future. To create this data set so that it can be incorporated into the County DFIRM, the following guidance documents were used: Data Capture Standards Technical Reference (**Reference 21**), FIRM Panel Technical Reference (**Reference 29**), Mapping Base Flood Elevations on Flood Insurance Rate Maps (**Reference 30**); Metadata (**Reference 31**); Physical Map Revision (PMR) (relevant sections; **Reference 32**); Flood Insurance Rate Map (FIRM) Database (**Reference 33**); and, Flood Insurance Rate Map (FIRM) Graphics (**Reference 34**).

In this section of the report the work maps are presented to illustrate the SFHAs in the study.

4.1. Floodplain Work Maps

Floodplain mapping was performed using results from the hydraulic analysis and the 2017 Quantum Spatial LiDAR. The workmaps are included in **Appendix B**, and they show the locations of the 1- and 0.2-percent-annual-chance flood event floodplain delineations along with the floodway delineations. Water surface elevation data, as well as floodway extents, were extracted from HEC-RAS using GeoHECRAS, version 2.7. GeoHECRAS was also used to produce rough floodplain delineations. These rough delineations were manually smoothed and adjusted to ensure reasonable floodplain delineations and to account for hydraulic features such as backwater, islands, or other appropriate features.

At some hydraulic cross sections, mapped floodplain and floodway topwidths may not exactly match modeled floodplain and floodway topwidths. These apparent discrepancies have multiple causes, depending on the cross section. Some of the common reasons for apparent map-model discrepancy include:

- All small islands are removed from the mapping – this is a standard FEMA practice to account for uncertainty around the islands, and because many islands are not visible at the FIRM scale. Large islands in the floodway where the average ground surface is less than 0.5 foot above the BFE were also not mapped, in order to retain floodway capacity.

- Hydraulically disconnected areas, which occasionally impact the model topwidth, are not mapped

- Mapping at a cross section can be influenced by another flooding source

- Differences can be caused by rapid expansion or contraction of the floodplain width in the model – i.e. – one cross section depicts flow wide across the entire low valley of the floodplain, and the next cross section depicts all flow contained in the channel. However, in reality, all flow would not immediately be directed to the channel. In these instances, engineering judgment was used to create a realistic floodplain.

At many locations, engineering judgment was critical in determining the appropriate floodplain and floodway boundaries.

4.2. Tie-In Locations

This study is part of a broader watershed-scale update to the flood studies within the Jefferson River watershed. The broader Jefferson River watershed effort includes both new studies and complete updates to existing studies within the watershed. The Jefferson River portion of the Three Forks study ties into a new study that is in progress for the Jefferson River with overlap between the two studies in the vicinity of Meridian Road bridge. Both studies utilize the same topographic data, hydrologic data, and hydraulic modelling methods and thus have good agreement between the studies. The downstream extent of the Jefferson River analysis ties into the effective Zone A SFHA downstream of the confluence of the Jefferson and Madison River. Similarly, the upstream extents of the Madison River portion of the Three Forks study area ties into a new study that is in progress on the Madison River in the vicinity of Climbing Arrow Road bridge. As with the Jefferson River, both studies utilize the same topographic data, hydrologic data, and hydraulic modelling methods and have good agreement between the results. There is also overlap between the two studies in the area of Climbing Arrow Road bridge. The downstream extent of the Madison River portion of the Three Forks study is at the confluence with the Jefferson River and ties into the effective Zone A SFHA downstream of the confluence. The effective SFHA at the downstream extent of the Madison River study shows significant influence from the Gallatin River floodplain, and the Madison River floodplain will tie into this Zone A area.

5. Flood Insurance Study

FEMA's KSS (**Reference 20**), Guidance for Flood Risk Analysis and Mapping - Flood Insurance Study Report (**Reference 25)**, and Flood Insurance Study (FIS) Report Technical Reference – Preparing FIS Reports (**Reference 26**) were followed to create the products in this section of the report. The FIS components included in **Sections 4.1 and 4.2** were created using FEMA's latest format specifications.

5.1. FIS Text

The relevant FIS tables have been populated with data from this study. The FIS information is in **Appendix J**.

5.2. Floodway Data Tables

The Floodway Data Tables are in **Appendix K** of this report. Footnotes have been added where appropriate to denote cross sections where special considerations cause differences between the information reported in the Floodway Data Tables, the HEC-RAS model, or the Hydraulic Work Maps. These additional footnotes have been added to the Madison River Floodway Data Tables to identify how ice affected BFE's and open water flow BFE's are presented (**Section 3.15**).

5.3. Water Surface Elevation Profiles

The water surface elevation profiles depict the 10-, 4-, 2-, 1-, and 0.2-percent annual chance flood events, along with the "1%+" annual chance event are included in **Appendix L** of this report. Two sets of profiles are presented in this Appendix for the Madison River. The first set of profiles represent the "With Levee" scenario results and include the ice jam surcharge as described in report **Section 3.13** and **Section 3.14**. The second set of profiles are presented to reflect the "Without Levee" scenario results (**Section 3.13**), and only include the panels where the levee exists (Panels 01P – 24P). The "Without Levee" profiles also have the ice jam surcharge applied (**Section 3.14**).

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